

OPTICAL DATA TRANSMISSION APPARATUS AND METHOD**INVENTOR: HENRY F. TAYLOR**

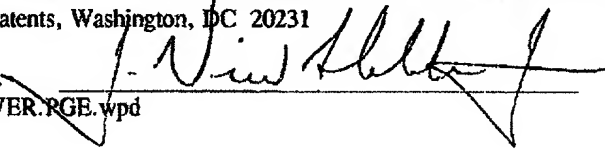
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Optical Data Transmission Apparatus and Method

Related Applications

The applicant claims the benefit of the provisional patent application filed on January 17, 2001, application number 60/262,334.

Field of the Invention

This invention relates to an optical data transmission apparatus and method. In particular, the invention relates, in a system for transmitting intensity modulated light waves over an optical fiber, to an apparatus and method including a cw laser, a phase modulator connected to the cw laser and an intensity modulator connected to the phase modulator.

Background of the Invention

Dispersion in optical fibers, which causes pulse broadening and data rate degradation, results from the dependence of propagation delay on optical frequency, as illustrated in Fig 1.

The upper plot shows schematically that the delay experienced by light propagating in a dispersive optical fiber is close to a linear function of optical frequency. Since the spectrum of a light pulse has a finite width, this dispersion causes pulse broadening. The middle drawing of Fig. 1 shows a single pulse being broadened by about a factor of three by propagation through the fiber, and the lower sketch shows multiple pulses running together so that "ones" cannot easily be distinguished from "zeroes" in a bit stream after passing through the fiber.

Dispersion is present in all fibers designed for wavelength-division-multiplex (WDM) communication systems. Although several methods to reduce the effect of dispersion are in use or under development, more effective and less expensive dispersion compensation is still a major need for present digital fiber optic systems. In comparison with the 10 Gb/s systems, which represent the state-of-the-art in commercial service, the deleterious effect of dispersion on the ability to demodulate a transmitted bit stream is magnified by about sixteen times in the 40 Gb/s

1 systems now under development. Prototypes of 40 Gb/s systems produced by companies such as
2 JDS Uniphase and Codeon are presently being evaluated by potential customers, and this new
3 technology is expected to be widely deployed for the first time during 2002.

4 Thus, there is a need in the art for a simple method for on-off modulation of a light beam so that
5 short pulses are produced after propagation through a dispersive fiber medium.

7 **Summary of the Invention**

8 Accordingly, the optical data transmission apparatus and method of the present invention
9 includes, in a system for transmitting intensity modulated light waves over an optical fiber, a cw
10 laser. A phase modulator is connected to the cw laser and an intensity modulator is connected to
11 the phase modulator

12 In another embodiment of the invention, in a system for transmitting intensity modulated
13 light waves over an optical fiber, an optical data transmission apparatus includes a cw laser
14 conformed to emit light at substantially a single frequency. A phase modulator is connected in
15 series with the cw laser and is conformed to cause the phase of the light from the cw laser to vary
16 in substantially a quadratic manner as a function of time during a time interval T . An intensity
17 modulator is connected in series with the phase modulator, wherein the intensity modulator is
18 conformed to transmit or block the light from the phase modulator in accordance with an
19 intensity modulation scheme for transmitting binary data such that the transmitted light consists
20 of pulses of temporal width T during which the phase of the light varies in substantially a
21 quadratic manner as a function of time.

22 In another aspect of the invention, the phase modulator is conformed to adjust the
23 amplitude of the phase change of the light, subject to the constraint that the phase of the light
24 varies in substantially a quadratic manner as a function of time during the time interval T . In a
25 another aspect of the invention, the intensity modulator is selected from a group including Mach-
26 Zehnder and electro absorption modulators. In a further aspect of the invention, the phase
27 modulator is selected from a group including straight waveguides and slow wave waveguides. In

1 another aspect of the invention, a multiplicity of cw lasers each connected to a phase modulator,
2 each of which, in turn, is connected to an intensity modulator, is provided. An optical coupler is
3 connected to each intensity modulator and an optical amplifier is connected to the optical
4 coupler. In a further aspect of the invention, more than two cw lasers are provided in which the
5 frequencies of the more than two cw lasers are different from one another and the frequencies
6 emitted by the more than two cw lasers are in a progression with substantially equal frequency
7 spacing.

8 In a further aspect of the invention, four cw lasers are provided with a phase modulator
9 connected to each cw laser. An intensity modulator is connected to each phase modulator and a
10 four to one optical coupler is connected to all four intensity modulators. An optical amplifier is
11 connected to the four to one coupler.

12 In another embodiment of the invention, in a system for transmitting intensity modulated
13 light waves over an optical fiber, a method of producing pulses of light which are compressed in
14 temporal width by transmission over an optical fiber includes the steps of inputting a light wave
15 to a cw laser. A phase modulator is connected to the cw laser, the phase modulator conformed to
16 transmit a phase-modulated pulse of light adjusted for amplitude and width. An intensity
17 modulator is connected to the phase modulator, the intensity modulator conformed to transmit a
18 phase-modulated pulse of light and to block light outside of the pulse of light of a particular
19 width.

20 In a another embodiment of the invention, in a system for transmitting intensity
21 modulated light waves over an optical fiber, a method of producing pulses of light which are
22 compressed in temporal width by transmission over an optical fiber includes the steps of
23 inputting light from a cw laser which emits light at substantially a single frequency. A phase
24 modulator is connected in series with the cw laser, where and the phase modulator causes the
25 phase of the light from the cw laser to vary in substantially a quadratic manner as a function of
26 time during a time interval T , such that the amplitude in temporal width T can be adjusted. An
27 intensity modulator is connected in series with the phase modulator, wherein the intensity

modulator is adjusted to transmit or block the light from the phase modulator in accordance with an intensity modulation scheme for transmitting binary data, such that the transmitted light consists of pulses of temporal width T during which the phase of the light varies in substantially a quadratic manner as a function of time, and the temporal width T can be adjusted.

Description of the Drawings

Other objects, features, and advantages of the present invention will become more fully apparent from the following detailed description of the preferred embodiment, the appended claims and the accompanying drawings in which:

FIGURE 1 is a schematic illustration of the effect of uncompensated dispersion in optical fiber systems;

FIGURE 2 is a schematic illustration of the optical data transmission apparatus of the present invention showing use of phase modulation and intensity modulation to produce a compressed pulse after transmission over a dispersive optical fiber;

FIGURE 3 is an illustration of the phase modulator of the present invention in the form of a straight waveguide;

FIGURES 4a and 4b are illustrations of a slow wave phase modulator of the present invention usually a uniform grating (4a) and a grating etalon (4b);

FIGURE 5 is a schematic illustration of the temporal dependence of optical power transmitted through a dispersive fiber;

FIGURE 6 is a schematic illustration of a preferred embodiment of the present invention for interleaving bit streams from multiple transmitters;

FIGURE 7 is a schematic illustration of the use of the invention illustrated in Figure 6 whereby a dispersion induced delay differential is used for interleaving parallel bit streams from four transmitters to produce a single serial bit stream after transmission through a dispersive fiber;

FIGURE 8 is a schematic illustration of a variation of the embodiment set forth in Figure 6 wherein a single phase modulator is utilized in conjunction with a four by one optical coupler; and

FIGURE 9 is a schematic illustration of an embodiment of the invention set forth in Figure 2 wherein the phase modulator follows the intensity modulator.

Detailed Description of the Invention

The preferred embodiment of the present invention is illustrated by way of example in Figures 2-9. With specific reference to Figure 2, the optical data transmission apparatus 10 of the present invention includes a cw laser 12. A phase modulator 14 is connected in series to the cw laser 12. An intensity modulator 16 is connected thereafter to the phase modulator 14. Figure 2 illustrates that intensity modulator 16 is connected to dispersive fiber 18.

The optical data transmission apparatus 10 of the present invention makes use of a combination of phase and intensity modulation acting on a continuous (cw) light wave 20 to produce pulses 22 which are compressed in temporal width by transmission over an optical fiber 18. The invention also provides for combining bit streams consisting of light pulses generated at a relatively low data rate to produce a single time-division-multiplexed bit stream at a higher data rate, as will be discussed more fully hereafter.

An arrangement of the invention for generating a single compressed pulse 22 is illustrated in Fig. 2. A continuous light wave 20 from a cw laser 12 passes through a phase modulator 14, which causes the phase ϕ of the light wave 20 to vary in quadratic fashion with time t according to the expression

$$\phi(t) = \phi_0 \left[1 - \frac{4(t - t_0)^2}{T^2} \right], \quad -.5T \leq t - t_0 \leq .5T \quad (1a)$$

$$\phi(t) = 0, \quad t - t_0 < -.5T \text{ or } t - t_0 > .5T \quad (1b)$$

Where t_0 is the time corresponding to the center of the phase modulation pulse, ϕ_0 is the amplitude of the phase modulation, and T is the temporal width of the phase modulation pulse.

After passing through the phase modulator 14, the light 20 is incident on an intensity modulator 16, which transmits the phase-modulated pulse and blocks light outside the pulse of width T . With an appropriate choice of the pulse amplitude ϕ_0 and width T , the pulse 22 will be compressed in time after passing through the fiber 10.

The intensity modulator 16 could be a Mach-Zehnder or electro absorption device of the type used in present-day communication systems or any type of intensity modulator now known or hereafter developed. The phase modulator 14 could be a straight waveguide 24 in an electrooptic material flanked by electrodes, as in Fig. 3. To produce larger phase shifts a slow wave structure 26 as in Fig. 4a or Fig. 4b might be utilized. In either case, the phase modulator 14 is driven by a voltage waveform, which is periodic in time to produce a phase shift, which is approximately a quadratic function of time during a pulse duration T .

The Fourier transform method is used to analyze the propagation of the pulse in the fiber 18 for the invention illustrated in Fig. 2. The electric field amplitude $f(z,t)$ of the modulated optical pulse as it enters the fiber at $z = 0$ can be written

$$f(0,t) = e^{i\phi(t)} \quad -.5T \leq t - t_0 \leq .5T \quad (2a)$$

$$f(0,t) = 0 \quad t - t_0 < -.5T \text{ or } t - t_0 > .5T \quad (2b)$$

where $\phi(t)$ given by eqns. 1a and 1b, and $|f(0,t)|$ has been normalized to unity for the duration of the pulse. The Fourier transform $F(z,\omega)$ at $z = 0$ can be written

$$F(0,\omega) = \frac{1}{\sqrt{2\pi}} \int_{t_0-.5T}^{t_0+.5T} f(0,t) e^{i\omega t} dt, \quad (3)$$

with ω the radian frequency given by $\omega = 2\pi\nu$, with ν the optical frequency. After the light propagates a distance L in the fiber, the Fourier transform can be written

$$F(L, \omega) = F(0, \omega) e^{i\mu\omega^2}, \quad (4)$$

where μ represents the effect of dispersion in the fiber given by

$$\mu = \frac{1}{2} \frac{\partial^2 \beta}{\partial \omega^2} \frac{L}{T^2}, \quad (5)$$

with β the propagation constant of the fiber mode.

The next step in the analysis is to determine $f(L, t)$ by calculating the inverse Fourier transform of $F(L, \omega)$ by evaluating the integral in

$$f(L, t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F(L, \omega) e^{-i\omega t} d\omega \quad (6)$$

The normalized temporal dependence of the optical power in the transmitted pulse $P(L, t)$ is given by

$$P(L, t) = |f(L, t)|^2 \quad (7)$$

Fig. 5 illustrates the temporal dependence of optical power transmitted through a dispersive fiber, as calculated by the Fourier transform method described above. In these plots, the width of the pulse incident on the fiber at $z = 0$ is T , and $t' = (t - t_0)/T$. Two cases are represented: $\mu = .02$ and $\phi_0 = -\pi$ rad, and : $\mu = .01$ and $\phi_0 = -2\pi$ rad. In both cases the quadratic phase modulation waveforms $\phi(t)$ are also plotted.

Calculated plots of transmitted pulse waveforms are given in Fig. 5. In the first case ($\mu = .02$, $\phi_0 = -\pi$), the width of the transmitted pulse is 50% that of the incident pulse. In the second case ($\mu = .01$, $\phi_0 = -2\pi$), the width of the transmitted pulse is 25% that of the incident pulse.

In these plots, dispersion is expressed in terms of the dimensionless parameter μ . To relate this to known (i. e., measured) parameters for optical fibers, we first note that

$$\Delta t = \frac{\partial^2 \beta}{\partial \omega^2} L \Delta \omega, \quad (8)$$

with Δt the temporal width of the transmitted light pulse, L the fiber length, and $\Delta \omega$ the spectral width of the pulse expressed in terms of radian frequency.

Normally, dispersion in fibers is expressed as a factor δ , with units of ps/(nm-km), such that

$$\Delta t' = (\delta L)' (\Delta \lambda)' \quad (9)$$

with $\Delta t'$ the temporal width of the transmitted light pulse in ps and $\Delta \lambda'$ the spectral width of the pulse in nm. The quantity $(\delta L)'$ has units of ps/nm. To convert this to standard mks units, we note that

$$(\delta L)' \text{ (ps/nm)} = (\delta L) \text{ (s/m)} \times (10^{12} \text{ ps/s}) \times (10^{-9} \text{ m/nm}) = 10^3 (\delta L) \text{ (s/m)}$$

Then, eq. (9) becomes

$$\Delta t = 10^{-3} (\delta L)' (\Delta \lambda), \quad (10)$$

with Δt in s, $\Delta \lambda$ in m, and $(\delta L)'$ in ps/nm.

The next step is to relate a wavelength change $\Delta \lambda$ to a change in radian frequency $\Delta \omega$. This is done by noting that $\lambda \nu = c$, with c the free-space speed of light, and $\omega = 2\pi \nu$. Thus,

$$\omega = 2\pi c / \lambda \quad (11)$$

and

$$\Delta \lambda = (\lambda^2 / 2\pi c) \Delta \omega \quad (12)$$

With this substitution, eq. (10) becomes

$$\Delta t = \frac{10^{-3}(\delta L)' \lambda^2 (\Delta \omega)}{2\pi c} \quad (13)$$

Comparing this equation to eq. (8), it follows that

$$\frac{\partial^2 \beta}{\partial \omega^2} L = \frac{10^{-3}(\delta L)' \lambda^2}{2\pi c} \quad (14)$$

Using numerical values $\lambda = 1.55 \mu\text{m}$ and $c = 3 \times 10^8 \text{ m/s}$, we calculate that

$$\frac{\partial^2 \beta}{\partial \omega^2} L = 1.275 \times 10^{-24} (\delta L)' \quad (15)$$

Finally, from eq. (5) it follows that

$$\mu = 6.37 \times 10^{-25} (\delta L)' / T^2, \quad (16)$$

where μ is dimensionless, the units of $(\delta L)'$ are ps/nm, and the units of T are s.

The results now make it possible to make some numerical calculations for cases of interest. First, we can generalize from the data of Fig. 5 that, to achieve a short pulse after propagating through a dispersive fiber, the desired value of μ is

$$\mu = .04 T_c / T, \quad (17)$$

and the corresponding phase shift amplitude is

$$\Delta \phi_0 = - .5 \pi T / T_c, \quad (18)$$

with T_c the width of the compressed pulse.

As an example, if $(\delta L)' = 150 \text{ ps/nm}$ and the width of the modulated pulse coupled into the fiber $T = 100 \text{ ps}$, then from eq. (16) $\mu = .0095$. From eq. (17), it follows that the width of the compressed pulse $T_c = 23.9 \text{ ps}$. From eq. (18), the required phase shift $\Delta \phi_0$ is $-2.09\pi \text{ rad}$.

Optical bit streams produced by the invention illustrated in Fig. 2 can be interleaved to produce multiplexed bit streams at a higher data rate, using the configuration of the invention illustrated in Fig. 6. Modulated light in the four transmitter channels is combined in a four by one optical coupler 26 and amplified optically in an optical amplifier 28 before transmission over a dispersive fiber 18. The four cw lasers 12 are tuned to operate at equally spaced frequencies ν_1 , ν_2 , ν_3 , and ν_4 , such that the dispersion-induced delay for adjacent frequencies is displaced by one bit period for the compressed pulses. For example, for propagation at a multiplexed data rate of 40 Gb/s, the bit period is 25 ps, requiring a wavelength spacing of 0.17 nm for the adjacent channels. Since a wavelength change of 0.8 nm corresponds to a frequency change of 100 GHz in the 1550 nm spectral region, the optical spacing for adjacent frequencies would be 20.8 GHz.

The manner in which the four data streams are interleaved is illustrated in Fig. 7. Assuming a fourfold compression of the optical pulses generated by each transmitter, bits from the first transmitter will arrive at the receiver in bit periods 1, 5, 9, ...; from the second transmitter in bit periods 2, 6, 10, ..., etc.

Again, Fig. 7 illustrates the use of dispersion-induced delay differential for interleaving of parallel bit streams from four transmitters to produce a single serial bit stream after transmission through a dispersive fiber 18.

In Figs. 2 and 6, the phase modulators 14 precede the intensity modulators 16 in the optical train. Applicant has determined that the order of these components can be reversed without materially affecting the system performance as illustrated in Fig. 9.

Additionally, in Fig. 6, the four phase modulators 14 located adjacent to the cw lasers 12 may be replaced by a single-phase modulator 14 located following the four by one optical coupler 28 as illustrated in Fig. 8. In that case, the single-phase modulator 14 simultaneously acts on all four multiplexed data channels.

Additional modification and permutations may be created as well. For instance, Fig. 6 shows multiplexed data within a single WDM channel. Two or more of these WDM channels

1 can be combined at the transmitter and separated at the receiver using standard WDM
2 components.

3 In short, the optical data transmission apparatus and method of the present invention
4 provides significant advantages over the prior art in at least three important areas: (1)
5 performance and cost of dispersion compensation, (2) simplicity and cost of multiplexing of data
6 channels, and (3) reduction in the speed requirements for optical modulators. Each of these is
7 discussed below.

8 Dispersion compensation is one of the top technology needs in high-data-rate, long-
9 distance optical fiber systems. First, there is a lot of installed fiber ("legacy fiber") with a
10 dispersion minimum at a wavelength near 1300 nm which is now being used at 1550 nm to take
11 advantage of lower fiber loss and the availability of optical amplifiers in that wavelength regime.
12 This fiber has dispersion so high (of the order of 25 ps/nm-km) that, even with state-of-the-art
13 compensation, the fiber cannot support transmission at 10 Gb/s over significant distances. The
14 technology disclosed here would be ideal for use with this legacy fiber.

15 For the past several years, fiber with a dispersion minimum near 1570 nm has been
16 installed for use in wavelength multiplexed systems operating in the 1530-1560 spectral band.
17 This fiber has much lower dispersion ($\approx 1 - 3$ ps/nm-km) than the legacy fiber at wavelengths of
18 interest, so less compensation is required for a given fiber length. However, compensation with
19 this newer fiber is difficult because of the variation in dispersion with wavelength ("dispersion
20 slope"). The techniques described in this disclosure could solve this problem for 10 Gb/s
21 systems by tuning the pulse width T and phase modulation amplitude ϕ_0 within each transmitter
22 to optimize the output pulse width for the dispersion experienced in that particular wavelength
23 channel.

24 In comparison with the 10 Gb/s systems, which represent the state-of-the-art in
25 commercial service, the deleterious effect of dispersion on the ability to demodulate a transmitted
26 bit stream is magnified by about sixteen times in the 40 Gb/s systems now under development.
27 The invention disclosed herein will be even more important at the higher data rate; e. g., in

1 combining four 10 Gb/s data streams to produce a single 40 Gb/s dispersion-compensated bit
2 stream, as in the example given above.

3 The ability to multiplex the bit streams optically (e. g., combining four parallel 2.5 Gb/s
4 data streams to form a single 10 Gb/s data stream, or to combine four parallel 10 Gb/s data
5 streams to form a single 10 Gb/s data stream) substantially reduces the cost of electronic
6 subsystems because they will not need to operate at such high speeds as in the conventional
7 systems.

8 Finally, the ability to use relatively low-speed modulators to generate higher-data-rate bit
9 streams favorably impacts the cost of the modulating devices and reduces their electrical power
10 consumption as well.

11 The end result of this invention is to provide a more effective and less expensive means
12 of transmitting data at high rates over dispersive optical fiber 18.

13 The invention makes use of a combination of phase 14 and intensity 16 modulation
14 acting on a continuous (cw) light wave 20 to produce pulses 22 which are compressed in
15 temporal width by transmission over a dispersive optical fiber 18. The invention also provides
16 for combining bit streams consisting of light pulses generated at a relatively low data rate to
17 produce a single time-division-multiplexed bit stream at a higher data rate.

18 The invention simultaneously addresses three major issues with high-data-rate fiber optic
19 communication systems - dispersion compensation, high-speed modulation of light, and
20 multiplexing. The method is suitable for very high data rate (10 Gb/s and 40 Gb/s) digital fiber
21 optic systems with fibers of arbitrary length and moderate-to-high spectral dispersion. The need
22 for expensive optical dispersion compensation equipment can be eliminated, and requirements on
23 high-speed optical modulators and electronic data multiplexors can be relaxed considerably.

24 The description of the present embodiments of the invention have been presented for
25 purposes of illustration, but are not intended to be exhaustive or to limit the invention to the form
26 disclosed. Many modifications and variations will be apparent to those of ordinary skill in art.
27 As such, while the present invention has been disclosed in connection with the preferred

1 embodiment thereof, it should be understood that there may be other embodiments which fall
2 within the spirit and scope of the invention as defined by the following claims.

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